

FLAME OSCILLATIONS IN NON-PREMIXED SYSTEMS DIFFUSION FLAMES AND EDGE-FLAMES

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Diffusive-thermal instabilities are well known features of premixed and diffusion flames. In one of its form the instability appears as spontaneous oscillations. In premixed systems oscillations are predicted to occur when the effective Lewis number, defined as the ratio of the thermal diffusivity of the mixture to the mass diffusivity of the deficient component, is sufficiently larger than one. Oscillations would therefore occur in mixtures that are deficient in the less mobile reactant, namely in lean hydrocarbon-air or rich hydrogen-air mixtures.

For diffusion flames the conditions for the onset of oscillations are more complex [1]-[2]. First, one may not speak of an effective Lewis number but rather consider two Lewis numbers, Le_F and Le_O associated with the fuel/oxidizer respectively. Furthermore unlike premixed systems, the compositions at the supply ends and the underlying flow conditions appear to be important parameters. A stability theory of a nominally planar flame shows that instabilities occur only when there is sufficient reactant leakage through the reaction zone. This would normally occur at high flow rates, or near-extinction conditions, when the Damköhler number D inversely proportional to the square of the characteristic flow speed is below a critical value D_c , so that $D_{ext} < D < D_c$ where D_{ext} identifies the extinction conditions. (A Burke Schumann flame sheet corresponding to complete combustion is therefore unconditionally stable.) Oscillations result when at least when one of the two Lewis numbers is larger than one, as shown in Figure 1, with the Lewis number of the reactant diffusing against the stream being of more relevant. We see that the parameter plane of Le_F versus Le_O is separated into two regions identified by excess/deficiency in available enthalpy in the reaction zone. Oscillations are possible only when the available enthalpy is in excess while cellular flames may occur when it is deficient. It is not necessary for both Lewis numbers to be larger than one, oscillations may occur when one of

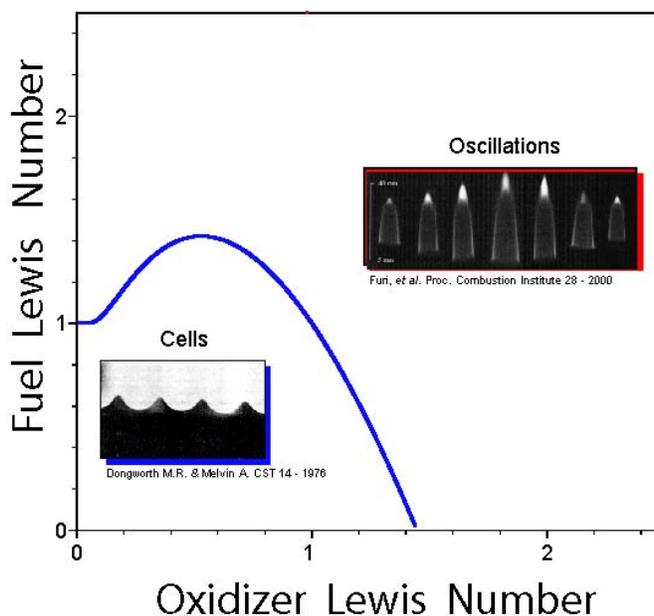


Figure 1

the two Lewis number is close to or even below one, provided the other is sufficiently larger than one. Another important parameter identified by the theory is the initial mixture strength ϕ defined as the ratio of the mass fraction of fuel supplied at the fuel boundary to the mass fraction of oxidizer supplied at the oxidizer boundary, normalized by their stoichiometric proportions. Oscillations are more likely to occur when the mixture in the reaction zone is relatively "rich" and hence characterized by an initial mixture-strength ϕ sufficiently larger than one. It should be noted that in practice ϕ is not an independent parameter; variations in mixture strength brought about by diluting the streams with an inert gas would also affect the values of the Lewis numbers. This suggests that the mixture strength is perhaps the most important parameter that determines whether oscillations will or will not occur. Finally, volumetric heat losses are also known to promote flame oscillations [2]-[4]; oscillations may occur under conditions where, in their absence, the flame remains stationary and stable.

The theoretical predictions summarized above are in general agreement with experimental results; see for example [5] where a jet configuration was used and experiments were conducted for various inert-diluted propane and methane flames burning in inert-diluted oxygen. Nitrogen, argon and SF₆ were used as inert in order to produce conditions of substantially different Lewis numbers and mixture strength. In accord with the predicted trend, it was found that oscillations arise at near extinction conditions, that for oscillations to occur it suffices that one of the two Lewis numbers be sufficiently large, and that oscillations are more likely to be observed when ϕ is relatively large.

The theoretical results reported above are based on a stability analysis of a nominally planar diffusion flame, so that when oscillations occur the flame appears to move back and forth normal to itself. Indeed, the diffusion flame surrounding a suspended fuel droplet [6] was seen to exhibit radial oscillations and for jet flames the whole flame expands and contracts during a cycle [5] in the axial direction. In other experiments where oscillations have been observed, whether in the laboratory or in microgravity environment, the flame has an edge which is seen to advance and retreat in a direction that more or less coincides with the diffusion flame trailing behind [7]-[9]. Edge-flames are two-dimensional structures that can be neither characterized as premixed nor as diffusion flames. Studies of oscillating edge-flames were carried out numerically by Buckmaster and co-workers [10] using a simple two-dimensional model of a flame traveling along an axis, with the concentrations of fuel and oxidizer specified in the transverse direction at two opposing ends. The edge results in their model from the fact that the fuel-supply is cut-off at a finite position. The calculations reveal that when the Damköhler number is sufficiently low and the fuel Lewis number sufficiently larger than one (the oxidizer Lewis number was taken to be equal to one) oscillations do occur. The results reported here are based on numerical calculations [11] that examine the dynamics of an edge-flame in a mixing layer. Two co-flowing streams, one of fuel and the other of oxidizer are separated upstream by a semi-infinite plate as shown in Figure 2. The flame established in the mixing layer formed

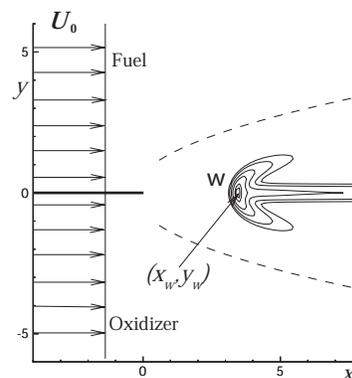


Figure 3

behind the tip of the plate consists of an edge-flame standing at some distance from the plate and a diffusion flame trailing behind. The objective is to examine the influence of the various parameters on the onset of oscillations and show that the edge-flame in this nonpremixed system possesses stability properties that share common features with those of diffusion flames reported above.

The position of the edge-flame (x_w, y_w), defined as the location where the reaction rate attains its maximum value, is plotted in Figure 3 as a function of the Damköhler number D for selected values of equal Lewis numbers both larger than one. The calculations reported in this case correspond to $\phi = 1$, so that the diffusion flame trailing behind lies along the y -axis as illustrated in Figure 2. For a given D the flame stands at a well-defined distance from the plate; it gets closer to the tip as D increases and gets attached to the plate when $D \rightarrow \infty$. The solid parts of the curve identify stable states while the dashed parts represent oscillatory states with an edge-flame advancing and retreating along the axis. Thus, oscillations occurs when $D < D_c$, or at high flow rates. The marginal state $D = D_c$ marked by a dark circle depends on the Lewis numbers and the mixture strength; the larger the Lewis numbers the larger D_c implying that oscillations are more likely to be observed when the Lewis numbers are sufficiently large. The temperature history at various locations along the axis (representing in this case the stoichiometric surface) shows that the oscillations are damped further downstream. This implies that it is primarily the edge of the flame that oscillates and that the oscillations decay along the trailing diffusion flame. Since in the absence of radiative losses the flame extends to infinity, far downstream combustion occurs along a Burke-Schumann flame sheet that, as discussed above, is absolutely stable.

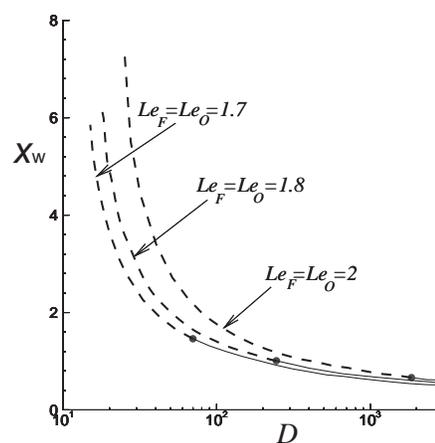


Figure 4

Although the results presented in Figure 3 considered equal Lewis numbers for both the fuel and oxidizer, they are nevertheless representative of situations where the Lewis numbers are unequal and larger than one. As suggested earlier, in non-premixed flames it is not necessary for both Lewis numbers to be larger than one; oscillations may occur even when one the two Lewis numbers is below one provided the other is sufficiently large. This is verified in Figure 4 which, similar to Figure 3 displays the position of the edge-flame as a function of D with $Le_F = 3$ and $Le_O = 0.8$. Note the sensitivity of the results to the Zeldovich number in this case. The figure in the insert shows the temporal variations of an unstable state which clearly exhibits a limit cycle with the edge moving back and forth nearly along the stoichiometric surface that lies in this case entirely in the fuel side ($y_w > 0$).

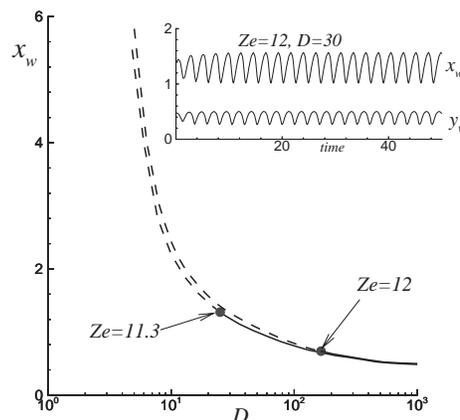


Figure 5

In the presence of radiative losses the diffusion flame trailing behind the edge-flame is quenched beyond a certain point and the flame is of finite extent. Complete extinction occurs when heat losses are excessive. This is shown in Figure 5, where the position of the edge-flame is plotted against the parameter b representing the ratio of radiative heat losses to chemical heat release. Total extinction occurs when $b \rightarrow b_{\text{ext}}$, the value of b where the curve becomes vertical. The dashed part of the curves, where to $b_c < b < b_{\text{ext}}$ correspond to oscillatory states. The calculations reported in this figure were carried out with unity Lewis numbers, in order to suppress diffusive-thermal effects [12]. The results imply that heat losses alone can trigger flame oscillations. Note that onset of oscillations requires a value of $\phi > 1$ and that oscillations occur primarily at near-extinction conditions.

Similar to diffusion flames edge-flames in mixing layers are characterized by two Lewis numbers, one associated with the fuel and the other with the oxidizer and by the mixture-strength ϕ based on the supply conditions. For oscillations to occur it is necessary for at least one of the two Lewis numbers to be larger than one and for the mixture to be “rich” in fuel. Volumetric heat losses promote and may even trigger flame oscillation. Oscillations occur only at sufficiently high flow rates, or near extinction conditions, when there is appreciable reactant leakage through the reaction zone. The mode of oscillation is a back and forth movement of the edge along the stoichiometric surface that decays further downstream along the trailing diffusion flame.

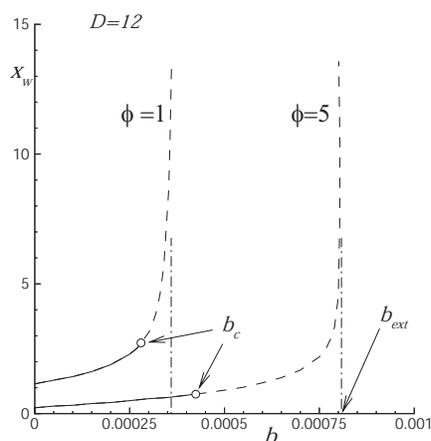


Figure 6

ACKNOWLEDGMENTS

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